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Control of Distributed Resources

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Introduction

On-site power generation is rising. Currently 35% of total US industrial electric power demand is met by on-site generation (Source Cambridge Research Associates). The trend is likely to accelerate. For industry with stable demand, it is usually cheaper to generate on-site to avoid charges for transmission, distribution or billing. The potential for smaller users, such as housing developments and office buildings to switch to on-site power is also high. A recent EPRI study indicates as much as 25% of new generation by 2010 will be distributed. The Natural Gas Foundation concluded that this figure could be as high as 30%

Distributed resources (DR) include a variety of energy sources, such as turbines, photovoltaics, fuel cells, and storage devices, with capacities in the 1 kW to 10MW range. Deployment of DR on distribution networks could potentially increase their reliability and lower the cost of power delivery by placing energy sources nearer to the demand centers. By providing a way to by-pass conventional power delivery systems, DR could also offer additional supply flexibility.

Emerging Technologies

The trends in technology points toward smallness, under the 1MW level. An excellent example are the small gas fired micro-turbines in the 25-100 kW range that can be mass produced at low cost. They are designed to combine the reliability of on board commercial aircraft generators with the low cost of automotive turbochargers. These systems are high speed turbines (50,000-90,000 rpm) with air foil bearings. They are small and use power electronic to interface with the load. Examples include AlliedSignal's 75-kW Turbogenerator, Allison Engine Co's. 50-kW generator and Capstone's 35 kW system.

Fuel cells are also well suited for distributed generation applications. They offer high efficiency and low emissions, but today's costs are high. Phosphoric acid cell are commercially available in the 200-kW range, while solid oxide and molten carbonate cell have been demonstrated.

In October 1997 the U.S. Depart of Energy and Arthur D. Little unveiled the "first-ever on-board gasoline powered fuel cell for the automobile". The possibility of using gasoline as a fuel for cells has resulted in a major development effort by the automotive companies. This work is focused towards the polymer electrolyte membrane (PEM) fuel cells.

In 1997 Ballard Generation Systems formed a strategic alliances with Daimler-Benz and Ford to develop the next generation of efficient and clean engines for the world's vehicles using the Ballard's PEM fuel cell. These engines are expected to meet the performance and range between refueling requirements of transportation vehicles at a projected fuel cell cost of $200 per kW. This together with much higher efficiency and without the significant polluting emissions associated with the internal combustion engine are expected to result in fuel cells capturing emerging markets.

Many other leading international companies are also using Ballard Fuel Cells including General Motors, Chrysler, Honda, Nissan, Volkswagen, Volvo, and Matsushita Electric.

By 2002, Ballard Power Systems expects to be selling a 250kW fuel-cell based generator at prices competitive with the grid to shopping malls and large commercial buildings. Cinergy Corporation recently placed a commercial order with Ballard for a 250-kW PEM fuel cell for stationary power.

Mixed fuel cell and micro-turbine systems are also available as distributed generation. In a joint DOE Westinghouse project a solid oxide fuel cell has been combined with a gas turbine creating a combined cycle power plant. It has expected electrical efficiency of greater than 70 percent with low CO_2 and NO_x and virtually zero SO_x. The expected power levels range from 250-kW to 2.5-MW.

Distributed resources include more than small generators and fuel cells. Storage technologies such as batters, ultracapacitors and flywheel play an important role. Combining storage with micro-sources provide peak power and ride-through capabilities during disturbances.

Storage systems are far more efficient than five years ago. Flywheel systems can deliver 700-kW for 5 seconds while 28-cell ultracapacitors can provide up to 12.5 kW for a few seconds.

Table 1. Distributed Generation Options

Type	Size (kW)	Efficiency	Cost $
Microturbine	25-100 kW	25-30%	~$350/kW
Fuel Cell	20-2000 kW	30-45%	~$2000/kW
Automotive Fuel Cell	30-200 kW	30-45%	~$200/kW
Microturbine / Fuel Cell	100-2000 kW	60-70%	
Battery	10-500 kWh	70-80%	~$500 kWh
Flywheel	2-100 kWh	70-80%	

Areas of Applications

The availability of small, low-cost, power sources provides opportunities for radical change in the structure of power delivery. One of the most basic is to provide firm power. This could be an isolated community, a commercial center or an industrial plant. It is highly probable that gas utilities, and ESCO will be approaching commercial centers and industries to provide firm power using distributed sources. Table 2 shows a firm power case study which was developed for serving a 250 kW load with six 50 kW micro-turbines. The annual load factor is assumed to 52% with 100% contingency using the redundant generator. The firm power of less than 5 cents per kWH is obviously competitive. If the natural gas is replaced with diesel at $0.85 per gallon the cost is $0.09 per kWH.

Table 2. Annual Cost for Firm Power Case Study (6-50 kW units for 250 kW load)

Total Investment	$105,000
-Amortization	$12,333/year
-Maintenance	$5,466/year
-Fuel	$36,438/year
Total Cost	$54,238/year
Cost/kWh	$0.0486
• Annual loading factor 52% • Amortization- 10 years at 10% interest	

For utility the two prime uses for micro-sources are for peak shaving at the distribution level and to deter or avoid the cost of increasing the distribution infrastructure. Mirco-turbines enable distribution to shave peaks through generation rather than demand side management (DSM) techniques. In addition to shaving peaks they also provide capacity for emergencies.[2]

Local generation not only increases overall system efficiency but also reduces investments in traditional generation, bulk transmission and distribution facilities. The utility can also serve incremental load growth in areas where there is a shortage of substation and/or distribution feeder capacity. For this to happen method for control and dispatch of 10s-to-100s of units are needed.

Major commercial and industrial users of electrical power pay demand charges to the utility. Micro-turbines could be used to reduce demand charges. In addition to saving in demand charges the turbines could be connected to the more critical loads to provide emergency power. Since all the micro-sources must have a power electronics interface they can all provide the quality of power provided by “Custom Power Devices,” such as active filtering, and voltage support during single and three phase disturbances.

These technologies require power electronics to interface with the power network and its loads. In all cases there is a D.C. voltage source which must be converted to an ac voltage or current source at the required frequency, magnitude and phase angle. In most cases the conversion will be performed using a voltage sources converter with a possibility of phase width modulation to provide fast control of voltage magnitude. This creates a very different situation when compared to synchronous generators. Fundamental frequency in a converter is created using an internal clock which does not change as the system is loaded.

Power electronic interfaces introduces new control issues and new possibilities. One large class is related to the traditional cogeneration problem. A system with clusters of micro-generators and storage could be designed to operate in both an island mode and as a satellite system connected to the power grid. In such systems load swings become a major issue. A step load will effect the system. In the case of a power electronics based source the dc bus voltage will decrease in response to the added load. Micro-turbines and fuel-cells have regulators which use the decrease in dc voltage to provide for increase energy input. Regulator response could be as slow as one to two minute requiring some form of storage during this period. This could be the kinetic energy of the turbines or battery storage. In traditional systems a load step of 20-25 percent compared to the generator rating is considered large, causing significant transients. Operation in the island mode implies the load level and generation rating are closer than when connected to the grid. This small margin compounds the problem of transients. This also implies that the generation needs to respond to larger than normal load changes (50-60%) without causing problems for the load and system.

Basic system problems include the control of the power feeder from the grid, speed of response of the micro-source, load sharing and tracking among the distributed resources, reactive power flow and power factor control and steady state and transient stability.

The control of inverters used to supply power to an AC system in a distributed environment should be based on information available locally at the inverter. In a system with many micro-sources communication of information between system is impractical. Communication of information may be used to enhance system performance, but must not be critical for system operation. Essentially this implies that the inverter control should be based on terminal quantities.

It is essential to have good control of the power angle and the voltage level by means of the inverter. Control of the inverter's frequency dynamically controls the power angle, and the flow of the real power. To prevent overloading the inverter and the micro sources, it is important to ensure that load changes are taken up by the inverter in a predetermined manner, without communication.

Basic Component Models

There are two basic classes of micro-source system; one is a D.C. source, such as fuel cells, photovoltaics, and battery storage, the other is a high frequency ac source such as the micro-turbine. In both cases the source needs to be interface to the ac network using a voltage sourced inverter as shown in Figure 1.

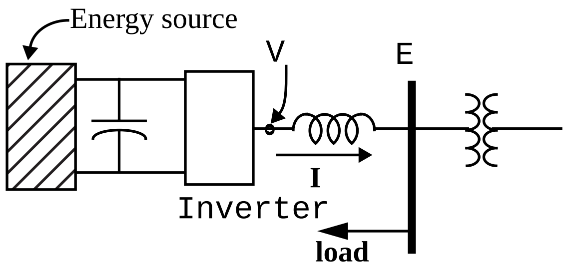


Figure 1. Interface Inverter System

As a minimum the inverter needs to control the flow of real and reactive power (P & Q) between the micro-source and the power system. The P & Q are coupled with P predominantly dependent on the power angle, δ, while Q is dependent on the magnitude of the converter's output voltage, V. It is also possible to independently control P and voltage E. The basic coupling equations are as expected.

$$P = \frac{VE}{\omega L}\sin\delta \qquad Q = \frac{V^2}{\omega L} - \frac{VE}{\omega L}\cos\delta \tag{1}$$

Inverter Controls

Consider the operation of a six-pulse GTO voltage sourced inverter connecting a stiff DC source to a stiff AC system through an inverter, as shown in Figure 1. The real and reactive powers are assumed to be the controlled quantities. Given set points for real and reactive power, P* and Q*, the inverter is controlled using the time-integral of the d-q space vector. Input phase voltages are transformed to the stationary d-q reference frame. The resulting d-q components are time integrated, resulting in the flux vectors $\overline{\Psi}_\upsilon$ and $\overline{\Psi}_e$, for the inverter and AC system voltages. This is a concept which is extensively applied to AC motors drives [3]. The control system for the inverter is given in Figure 2. The two variables that are controlled directly by the inverter are Ψ_υ and δ_p, where Ψ_υ and Ψ_e are the magnitudes of the inverter and AC system flux vectors respectively, and δ_p is the spatial angle between the two flux vectors. The vector $\overline{\Psi}_\upsilon$ is controlled so as to have a specified magnitude and a specified position relative to the AC system flux vector $\overline{\Psi}_e$. This control forms the innermost control loop, and is very fast. The inverter and AC system voltage space vectors are obtained from instantaneous voltage measurements and are available locally.

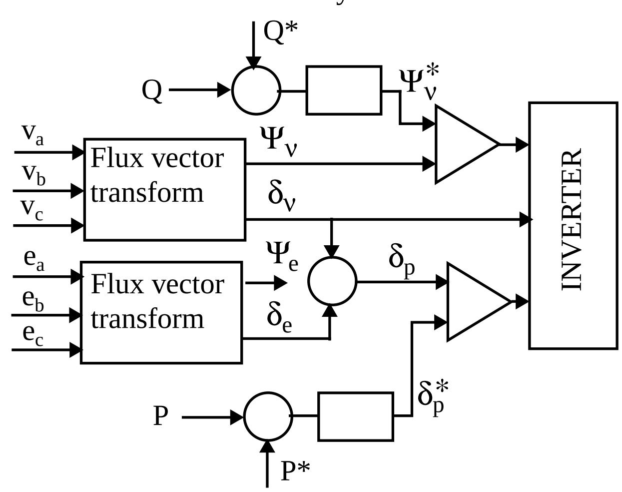


Figure 2. Inverter Control Scheme

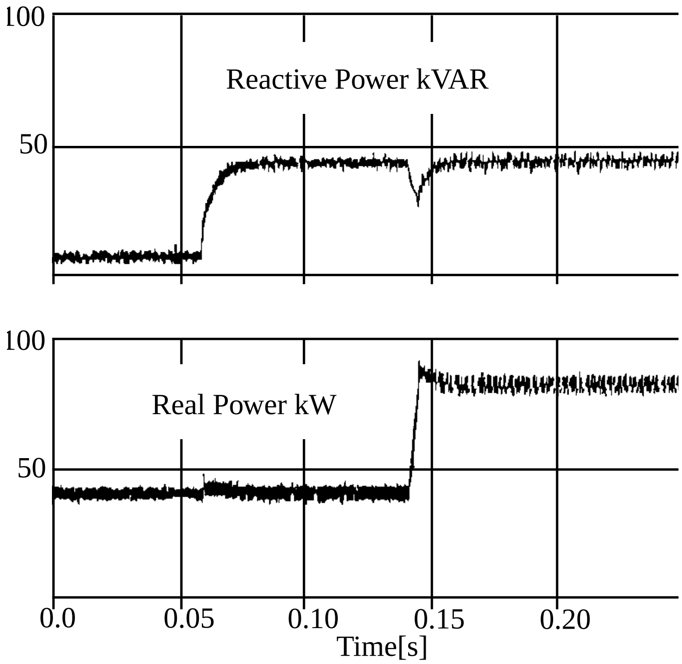


Figure 3. Response of Real and Reactive Power

Simulation results of the control scheme shown in Figure 2 are shown in Figure 3,[4]. The response of the inverter to step changes in set points Q* and P* are shown. It should also be noted that there is a disturbance in P when Q* is changed and a disturbance in Q when P* is changed. In each case, the regulators modified the set points δ_p^* and Ψ_υ^* to maintain the P and Q at the requested values. The disturbances last approximately 20 milli-seconds. These results assume a stiff D.C. voltage across the capacitor. In the actual system this is not the case requiring models of how the D.C. voltage changes as power demands change.

Mirco-turbine Models

Micro-turbines have a single rotating shaft, with the generator, air compressor, and turbine mounted on air bearings. The shaft operates at high speed without any lubrication. The power plant is a air-cooled, 2 pole permanent magnet generator. The air is brought through the generator, compressed before it flows through the recuperator into the combustion chamber and out through the recuperator. This allows the exhaust gases to preheat the incoming gases, which increases the efficiency of the system. The shaft turns between 15,000 and 90,000 revolutions per minute. The generator provides a high frequency AC voltage source (angular frequencies up to 10,000 rad/sec).

This require a power electronic interface between the micro-turbine and the AC load. This interface consists of AC to DC rectifier, a dc bus with a capacitor and a DC to AC inverter as shown in Figure 4.

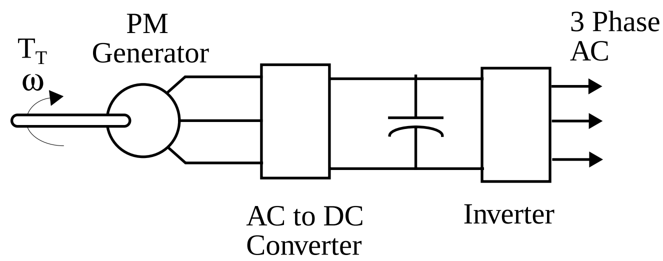


Figure 4. PM Generator with Power Electronics

The generator and rectifier can be modeled as a three phase, full-wave, diode bridge rectifier with the ac source being the PMG. The inductance is the equivalent inductance for each phase of the generator. It is also assumed that the losses can be neglected

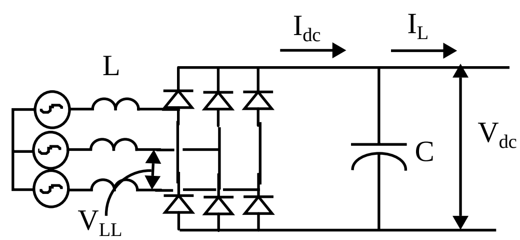


Figure 5. Rectification into a stiff DC bus

For an ideal, no-load PM Generator, the line-to-line voltage, V_{LL}, can be expressed as:

$$V_{LL} = K_v \omega \sin(\omega t) \qquad (2)$$

where K_v is the voltage constant and ω is the electrical angular frequency. Since most micro-turbine use 2 pole PMG the electrical and mechanical angular frequencies are equal. For operation at 90,000 RPM the angular frequency is, 9424 rad/s. The DC bus voltage regulation for full-wave rectifiers with constant current outputs can be expressed as:

$$V_{dc} = \frac{3}{\pi}|V_{LL}| - \frac{3\omega L}{\pi} I_{dc} \qquad (3)$$

Equations 2 and 3 allow the dc voltage to be expressed as a function of angular frequency and current.

$$E_g = V_{dc} + K_x \omega I_{dc} \qquad (4)$$

where the open circuit D.C. voltage E_g is:

$$E_g = K_e \omega \qquad (5)$$

The “K” constants are defined as;

$$K_e = \frac{3K_v}{\pi}[\mathrm{V/(rad/sec)}]$$
$$K_x = \frac{3L}{\pi}\ [\Omega/(\mathrm{rad/sec})] \tag{6}$$

Equation (4) provide the foundation for describing the electro-mechanical nature of the system. For a system with no losses the input power can be expressed as a function of I_{dc}.

$$P_m = V_{dc}I_{dc} = K_e\omega I_{dc} - K_x\omega I_{dc}^2 \tag{7}$$

From equation 7 the mechanical shaft torque for a loss-less system can be expressed;

$$T_m = \frac{P_m}{\omega} = K_eI_{dc} - K_xI_{dc}^2 \tag{8}$$

The mechanical system components can also be included through the inertia of the shaft, (J), turbine response and the governor. In this case the D.C. voltage is used as input to the governor. Turbine response is assumed to be first order with typical time constants in the 1-2 seconds range. The combined electro-mechanical system model for micro-turbine system is shown below. The damping of the turbine-generator is not shown, but could be included is a function of shaft speed. This model coupled with the inverter behavior and controls creates a complex, non-linear system.

Satellite & Island Operation

Distributed generation has the potential to increases over-all system efficiency, but can also reduces investments in distribution facilities. Incremental load growth can be accommodated in areas where there is a shortage of sub-station and/or distribution feeder capacity with out investment in either. For this to happen methods for placement of 10s-to-100s of small generators, and their control and dispatch needs to be developed.

Fuel to power conversions rates for fuel-cell and micro-turbine are greater than 2 seconds. For many loads this is too slow and would cause failures. One solution is to add storage to the system. This could be on the D.C. bus or the ac system. In either case there is additional equipment and cost. Another approach is to use the distribution sys-tem to provide the initial power needs resulting from a load change. This results in a effective control system for micro-sources.

Consider a satellite system where the distribution feeder and substation are operating near their ratings with many micro-sources near the loads. The basic operation requires that the feeders are not overloaded and the loads see a fast response to their changes in power needs. This can be achieved using a control strategy which holds the feeder power fixed except during load changes. Fast load tracking is provided through the feeder with the micro-sources taking up the new load on a slower time constant.

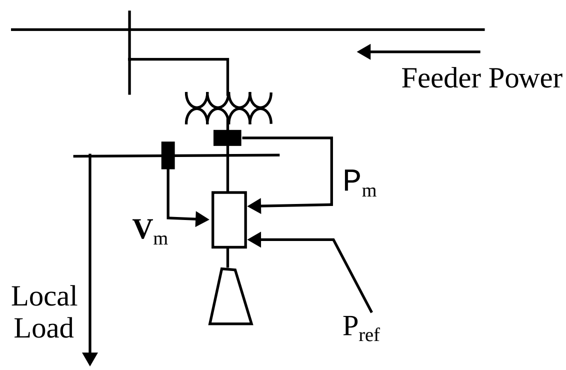
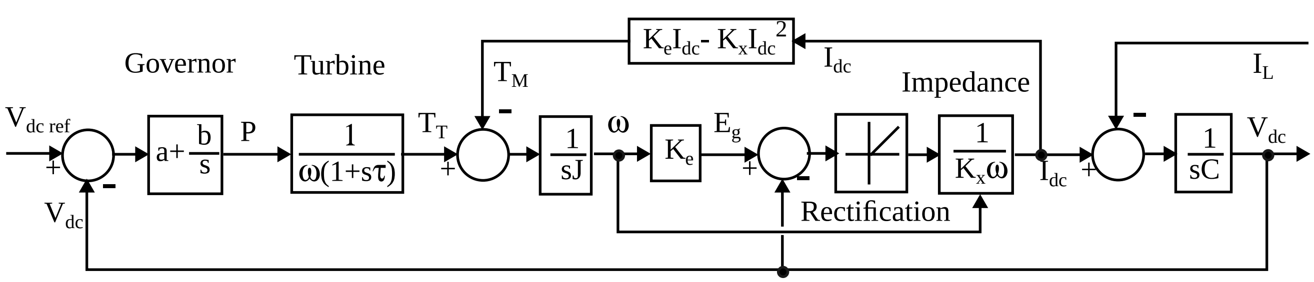


Figure 6. Local Voltage and Power Flow Control

This concept is shown in Figure 6, where P_m is the power through the transformer and P_{ref} is the desired power sup-plied by the feeder to the local load. The load and micro-turbine are assumed to be on a lower voltage bus. The power flow from the feeder rather than the load power is controlled. For example assume that the maximum local



Combined Electro-Mechanical System Model for Mico-turbine System load is 100 kW of which 30 kW is supplied by the feeder and 70 kW is supplied by the micro-turbine. The micro turbine output power is controlled to hold the feeder power to 30 kW for a range of load levels. Consider the case where the load increases from 50 kW to 100kW. For the 50 kW load level the feeder provides 30 kW and the micro-turbine 20 kW. When the load increase from 50 kW to 100 kW the initially power is provided by the feeder with the micro-turbine ramping up to 70 kW over several seconds forcing the feeder power back to 30 kW. The feeder power reference, P_{ref}, can also be re-dispatched to control the overall power flow as required by the total system.

Micro-sources or storage can also limit voltage disturbances within milli-seconds provided the D.C. capacitor is correctly sized. These techniques are the same as used by static VAR compensators which use no real power.

In addition to reducing the investment in distribution feeders and substation capacity, distributed resources can also provide emergency power during loss of the feeder. In this case the cost and control problems are increased.

A island system is shown in Figure 7. It is assumed that a battery or ultracapacitors is included on the D.C. bus to insure fast response to any power changes. Capacitors have also been added to the ac bus to insure stable ac voltages with the loss of the ac system. The basic system needs for island operation are;

- Adequate storage to allow for fast load tracking.
- Incorporation of frequency droop methods to insure load sharing between micro-sources
- Provide stable ac voltage control through ac capacitors and inverter action.

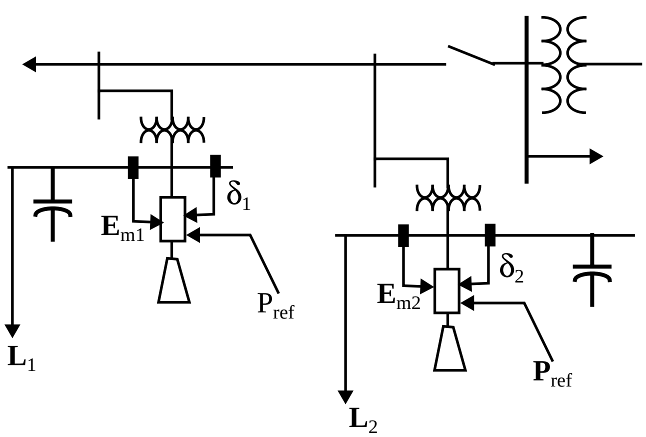


Figure 7. Island Operation

Power sharing is achieved through a frequency droop in ω_i at each inverter based on loading. If the inverter frequencies are less than ac system and different, $\omega_0 > \omega_1 > \omega_2$ the phase angle between the two buses will increase, changing the power flow between loads 1 and 2.

To implement this function the reference points ψ_υ^* and δ_p^* in Figure 2 need to include the change in ω and $\mathbf{E}$ due to droop. To determine δ_p^* the local frequency setting, ω^* determined by the power droop, is integrated to obtain a reference for the position δ^* of the AC system voltage vector $\mathbf{E}$ across the capacitor. This is compared with the actual position δ of $\mathbf{E}$. The error is used as input to a P-I regulator, which creates the reference δ_p^* .This replaces the power order. A similar droop in the set point for voltage magnitude, ψ_υ^* , as a function of reactive power can also included in the control system.

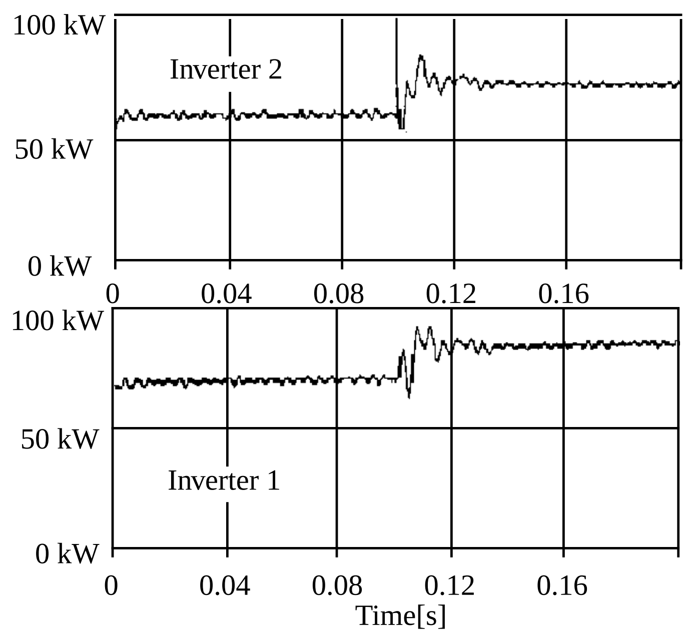


Figure 8. Response of Real Power

Figure 8 shows the response of the two sources when the load, L_2, is increase by 40%. Inverter 1 carries a larger share of the real power, since it has the smaller droop. The response of reactive power and ac voltage are shown in Figure 9 for the same change in load.The voltage is the line-to line voltage across at the capacitors on inverter 1. The oscillations are formed by the two capacitors and the feeder line inductance. Active damping can be included to hold these oscillations to a minimum, but for too large of a droop the systems will become unstable.

Power Quality Improvement

Small power sources increase reliability and power quality by allowing them to be placed near the load. This provides for a stiffer voltage at the load and uninterruptible power supply functions during loss of grid power. The power electronics interface can also control voltage dips and unbalances. Currently systems for controlling volt disturbances use a voltage sources inverter which injects reactive power into the system to achieve voltage correction. One method is to inject shunt reactive current, the other is to inject series voltage. These systems are effective in protecting against single phase voltage drops (or swells) due to distant faults or unbalanced loads. These systems are costly, complex and are needed only during voltage events. The remaining time they are in standby.

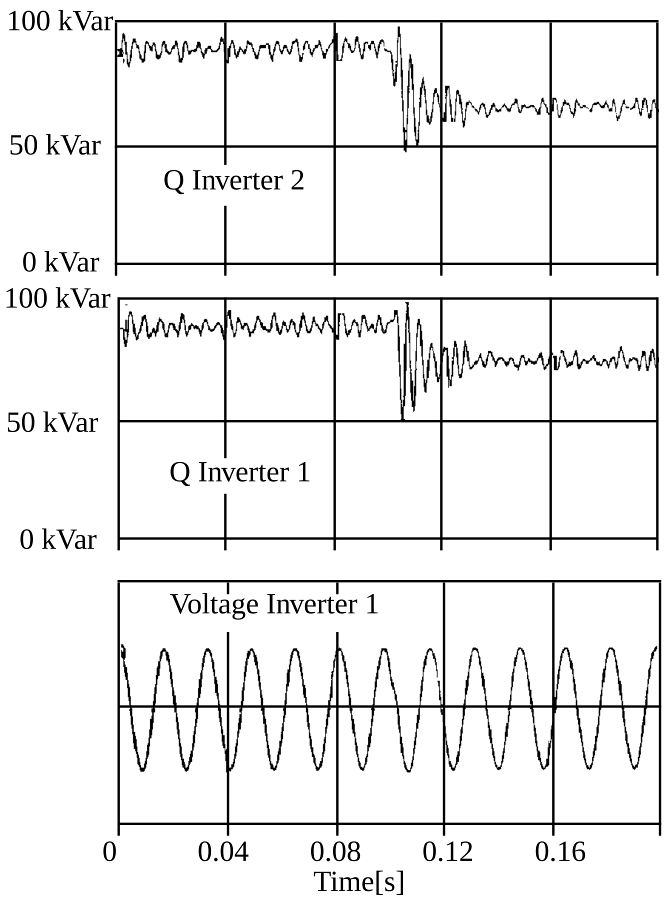


Figure 9. Reactive Power and Bus1 Voltage

With the addition of more complex controls and a higher converter rating a mirco-source can provide real power and protect against voltage drops and swells. This has the potential of becoming the ideal power quality device.

An example of the effectiveness of such a power electronics system (STATCON) in holding voltages constant for an induction motor load during a 3-phase fault is shown in Figure 10. The substation circuit breaker for the faulted feeder is opened at T=0.05 sec. When the STATCON is not present, the phase voltages at the regulated bus rapidly decay in voltage. The induction motor rotor speed drops and the frequency of the voltage decreases correspondingly. At T=0.15 sec, the circuit breaker is reclosed and the motor begins to slowly accelerate.

When the STATCON is present, the phase voltages at the regulated bus remain close to 1.0 pu for five cycles. The induction motor slows down slightly, releasing some of its kinetic energy and the STATCON's phase-locked loop tracks this frequency shift in the phase voltages. The STATCON's D.C. bus capacitor is being discharged to provide the additional energy for the load.[5] It is clear that a micro-source can use these techniques to control both real power flow and voltage disturbances at the load.

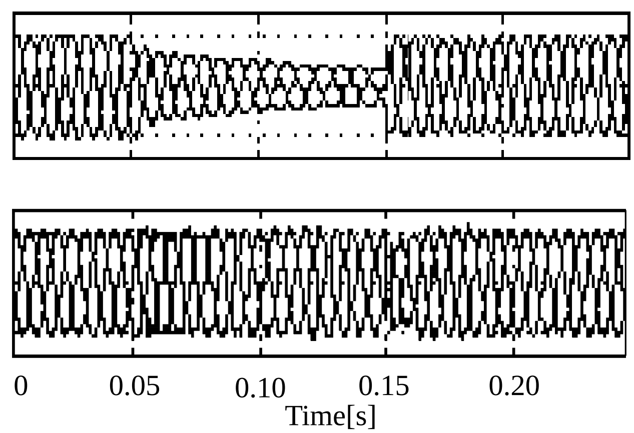


Figure 10. Three Phase Fault Voltage

Conclusion

This paper has focused on the potential of distributed resources to reduce the cost of electrical energy and improve the quality of the power. Key characteristics are;

- Such systems will be highly distributed.
- There will be a greatly reduced need for transmission
- Most control will be local and real time.

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